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High pressure electric discharge convection laser: a preliminary study

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HIGH PRESSURE ELECTRIC DISCHARGE CONVECTION LASER, A PRELIMINARY STUDY

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Monterey, California

THESIS

HIGH PRESSURE ELECTRIC DISCHARGE CONVECTION LASER, A PRELIMINARY STUDY

by

Joseph Richard Osani

September 1974

Thesis Advisor: O. Biblarz

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In this project, the fabrication and feasibility demonstration of a continuous flow, electric-discharge convection laser (EDCL) using a mixture of CO_2, N_2, and H_2O at atmospheric pressure was attempted. Electric discharge studies in air and nitrogen using a turbulence stabilization technique formed a large part of this project. Controlled turbulence can stabilize gaseous electric-dis-

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High Pressure Electric Discharge Convection
Laser, A Preliminary Study

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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September 1974

ABSTRACT

In this project, the fabrication and feasibility demonstration of a continuous flow, electric-discharge convection laser (EDCL) using a mixture of CO_2, N_2, and H_2O at atmospheric pressure was attempted. Electric discharge studies in air and nitrogen using a turbulence stabilization technique formed a large part of this project. Controlled turbulence can stabilize gaseous electric discharges as previously demonstrated, and the discharge studies of this project represent an application of such controlled turbulence to increase the discharge power of the laser. In this preliminary study, no laser action was detected. Several reasons for this lack of laser action are suggested.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure

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I. INTRODUCTION

Low pressure, electric-discharge convection lasers using the fast flow of a mixture of CO_2, He, and N_2 have been successfully operated (Ref. 1). In our work, the choice of the electric-discharge pumped laser over other types of pumping mechanisms for an atmospheric pressure laser is made because the system envisioned incorporates the laser in a closed-cycle wind tunnel, and the electric discharge pumping scheme offers the least contamination (Ref. 1).

Electric-discharge lasers have been demonstrated at atmospheric pressure (Ref. 2) using various discharge stabilizing techniques. The TEA laser uses a unique electrode design (Ref. 3) as well as a large proportion of helium to allow for high amounts of power to be coupled into the gas mixture. Discharge stabilization using some turbulent flow has been demonstrated with an electric laser operating at reduced pressure (Ref. 1). This thesis project investigates the feasibility of using a turbulence-stabilized, electric-discharge operating at atmospheric pressure to pump a gas mixture consisting of CO_2, N_2, and small amounts of water. The higher pressure is desirable in order to simplify the design and to couple more power into the laser mixture resulting in a higher infrared power output. The high pressure creates severe problems,

however, with the electric discharge. Most carbon-dioxide lasers use a mixture of CO_2, N_2, and He. The He is added to aid in the discharge stabilization and to also depopulate the lower laser level (Ref. 4). This is necessary in a slow flow system for the laser action to be continuous. It has been concluded from low power discharge work (Ref. 5) that because of the fast flow and because of the turbulence in the discharge region the helium could be omitted. The fast flow would carry the CO_2 molecules in the lower laser level out of the laser cavity and replace them with excited CO_2 molecules at a rate fast enough to sustain laser action. The amount of water in the system should be small enough to aid in the depopulation of the lower laser level without causing the harmful effects of large amounts of water (Ref. 6). Turbulence has the potential for stabilizing the discharge enough to allow the coupling of sufficient power into the gas mixture without the helium.

The long range goal of this project is the feasibility demonstration of a CW, electric-discharge convection laser operating in a closed system at atmospheric pressure (Ref. 7). The closed cycle compressor was not available at this time so a blow-down system using bottled gas was constructed. The run time available at realistic flow rates was very limited. The gas was exhausted, not recycled. The main emphasis is to demonstrate that enough power can be pumped into the laser mixture using the turbulence-stabilized discharge to cause the mixture to lase. The power output of this blow-down system should be low because it is a

scaled down model but it is felt that high optical power could be obtained using a larger discharge region and a higher flow velocity.

The laser system was constructed using materials and componets available here at the Naval Postgraduate School. The nitrogen flow system is limited by the delivery rate of the regulator described in Section II. The previous discharge work in air (Ref. 7) was at a flow velocity of 200 ft/sec, while the maximum flow velocity in nitrogen was less than half this value.

II. EXPERIMENTAL APPARATUS

A. GENERAL DESCRIPTION

The apparatus consists of a flow system for the gases with associated measuring equipment, the electric discharge system, and the laser system. In essence, two types of gas were available, namely, atmospheric air and technical grade water-pumped nitrogen which is better than 99.9 percent pure. Carbon dioxide was introduced into either flow in a manner which is described below. While the tests in air were not expected to produce lasing action, they served as a comparison with previous data (Ref. 7) on discharges with essentially the same apparatus. The gases were supplied from compressed gas bottles except for the air which flowed from a Carrier three-stage centrifugal compressor capable of delivering 4,000 cubic feet of air per minute at maximum pressure ratio of two. The laser system including the cavity section, windows, mirrors, detector, etc., represents the most novel feature of this thesis. Figure 1 is a photograph of the experimental set-up.

B. FLOW SYSTEM

1. Nitrogen Flow System

The nitrogen supply was connected to 9x9 inch cross section plenum through a valve, regulator, and flowmeter as shown in Figure 2. The plenum, nozzle, and discharge

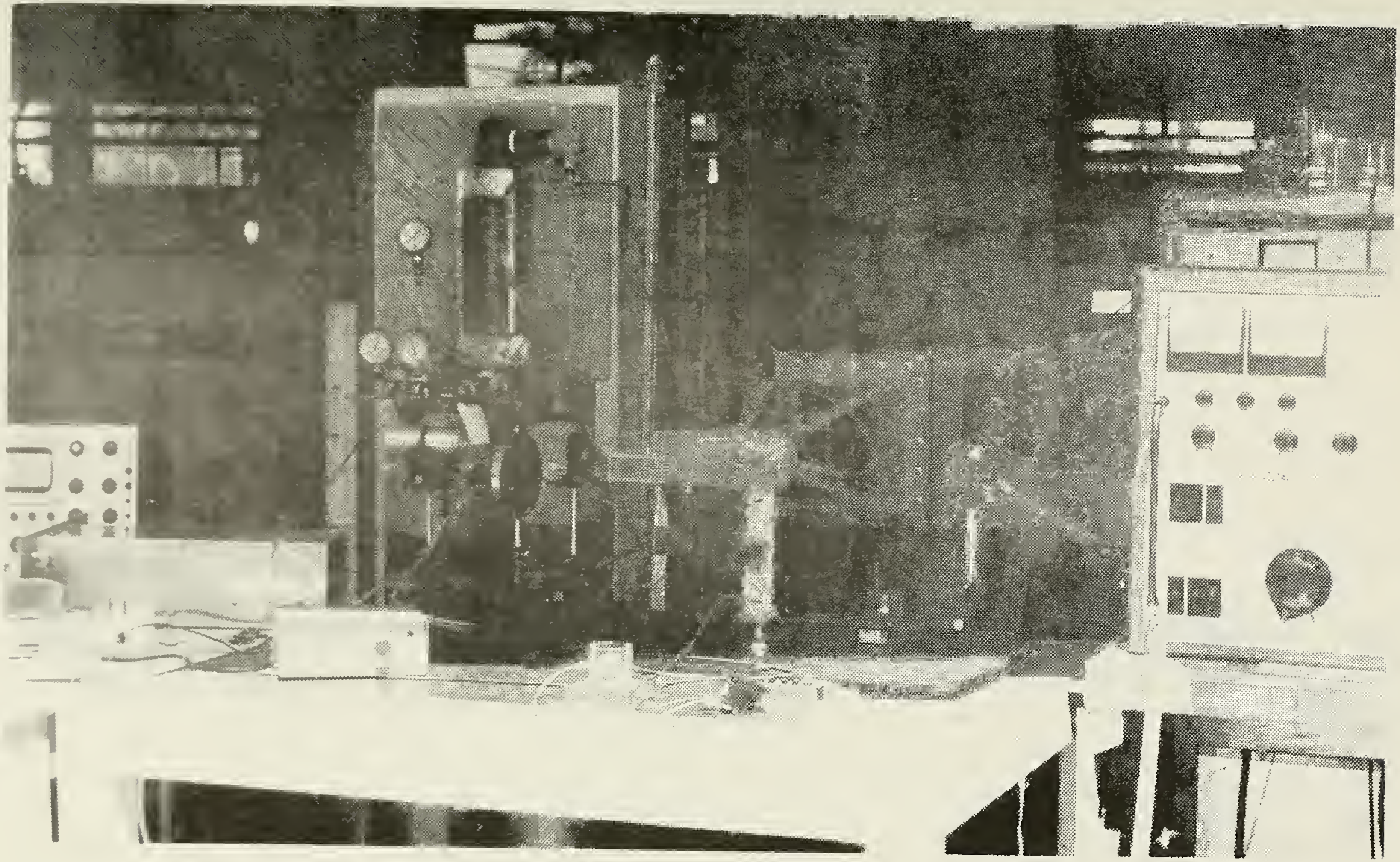


Figure 1. Experimental Set-up

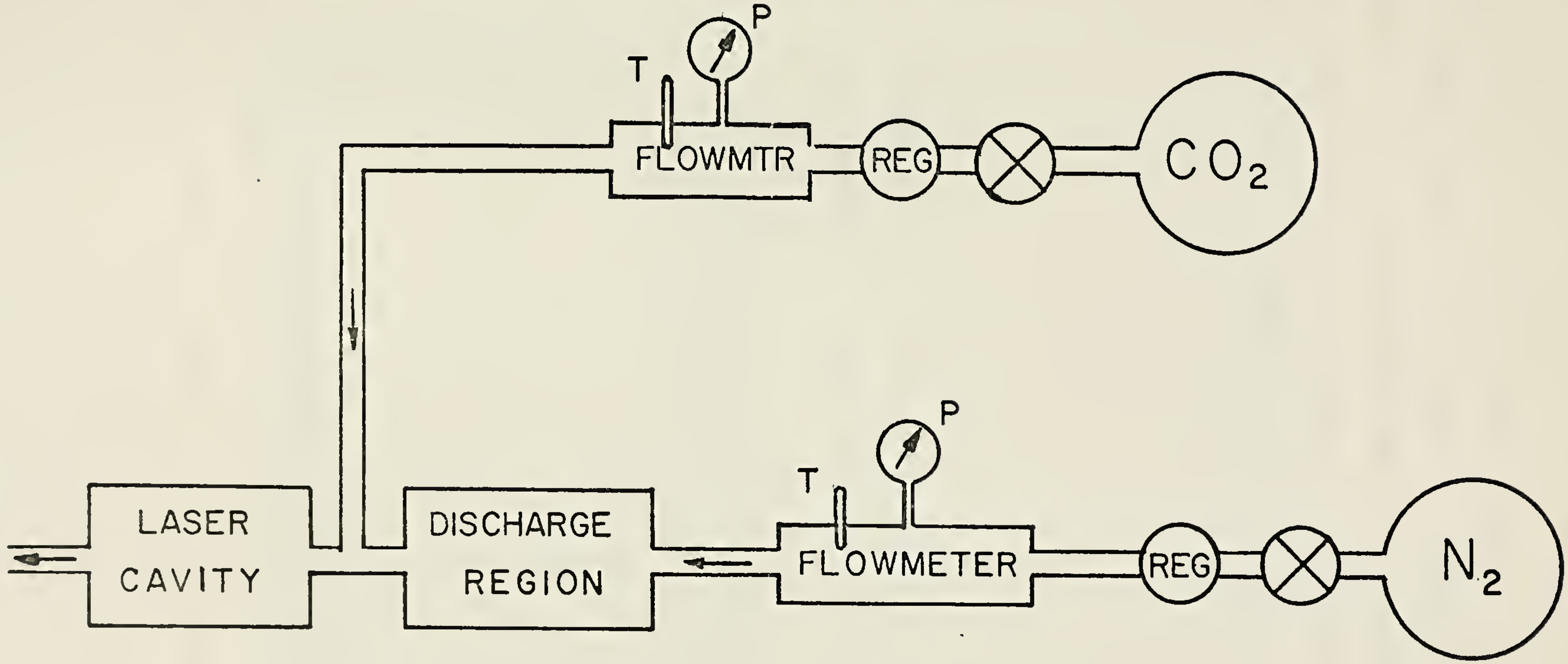


Figure 2. Schematic Representation of the EDCL Set-up

section used were designed as part of a closed cycle wind tunnel (Ref. 7). The nitrogen supply consists of eight 184 standard-cubic-foot bottles pressurized to 1800 psi connected to a common manifold. The regulator is a Grove dome-loaded, high flow regulator with 3500 psi inlet and 3000 psi outlet pressure. The nitrogen flowmeter is a 2 inch orifice-type flowmeter with 1.4 inch diameter orifice. The differential pressure across the orifice was connected to a differential-pressure transducer whose output drove the Y axis of an X-Y plotter. The X axis was driven by the current through the discharge section. This arrangement was deemed necessary because of the short run times available. Other methods of obtaining the I-V data for the changing flow rates were too slow and cumbersome. After passing through the flowmeter the nitrogen flowed through the plenum into a 10 to 1 area ratio nozzle. The turbulence generating screens were connected to the downstream end of the nozzle. After passing through these screens the nitrogen flowed into the discharge region and then into the laser cavity from which it was exhausted to the atmosphere.

The turbulence screens (Figure 3) consist of a phenolic plate with 0.25 inch diameter holes and a nylon mesh with 0.008 inch diameter nylon whose mesh spacing was 0.04 inch. According to Ref. 7, this screen combination offered the maximum discharge power of all the screens tested. Another screen was tried but did not give

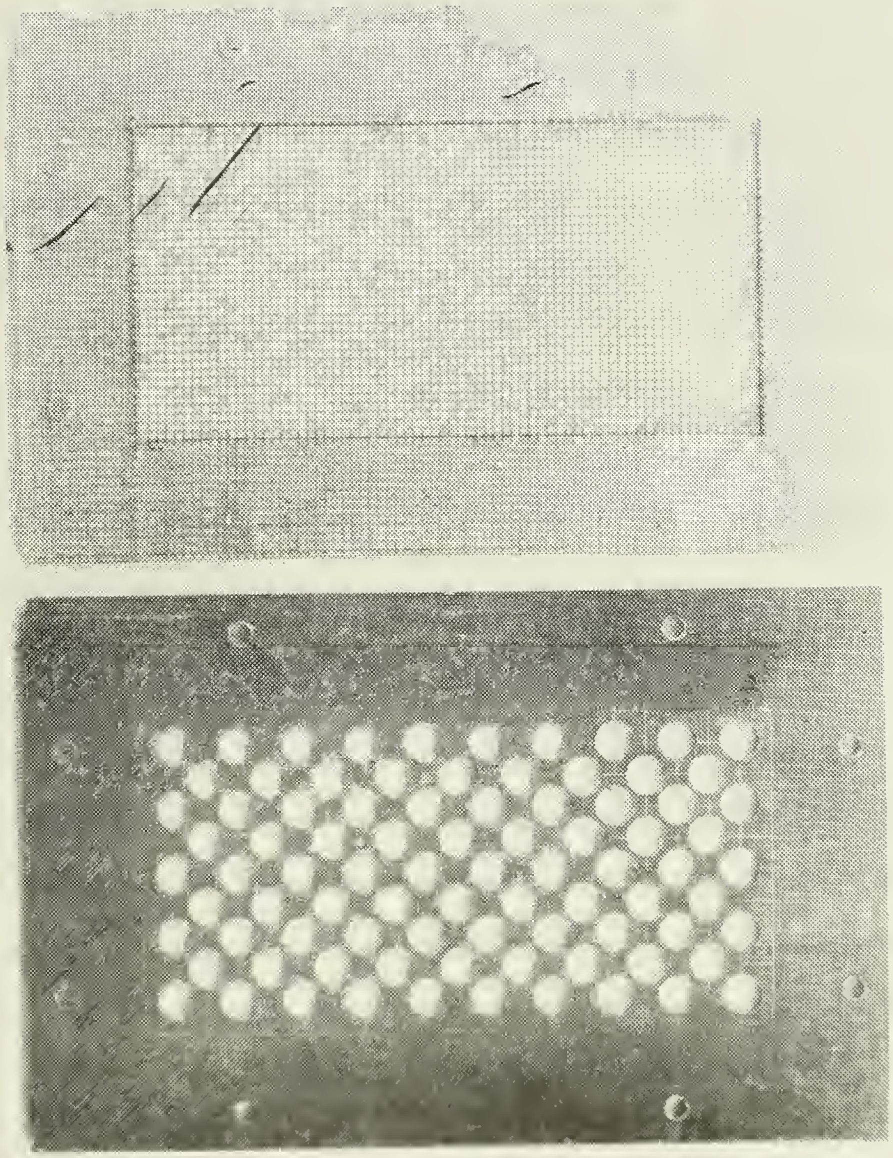


Figure 3. Turbulence Screens

sufficient discharge power when compared to the set shown in Figure 3.

2. Carbon Dioxide Flow System

The carbon dioxide flowed from one 50 pound bottle through a valve, regulator, and flowmeter into the airfoil electrode which is described in Section II C. The CO_2 flow was much less than the nitrogen flow; and a Fisher/Porter Rotameter whose capacity was 360 scfm was available for measuring the carbon dioxide flow. The same type of Grove regulator was used for the CO_2 as for the nitrogen. The airfoil electrode served two functions. First, it allowed the injection of carbon dioxide downstream from the discharge and second, it served as one electrical connection to the discharge supply.

C. ELECTRIC DISCHARGE

The discharge region consists of a 2x4 inch by 2 inch long plexiglass wind tunnel section with 3 rows of 5/8 inch long by 0.0626 inch diameter pin electrodes connected to a common airfoil as the upstream electrode and four hollow 1/2 inch cord by 4 inch span airfoil sections as the downstream electrode. The electrode design is shown in Figures 4 and 5. The turbulence screens were 1/2 inch upstream from the pin electrode and the airfoil electrode was 2 inches downstream from the pin electrode. The airfoils were hollow with slotted trailing edges to allow for the injection of carbon dioxide. The carbon dioxide is injected at this point in the flow system to improve

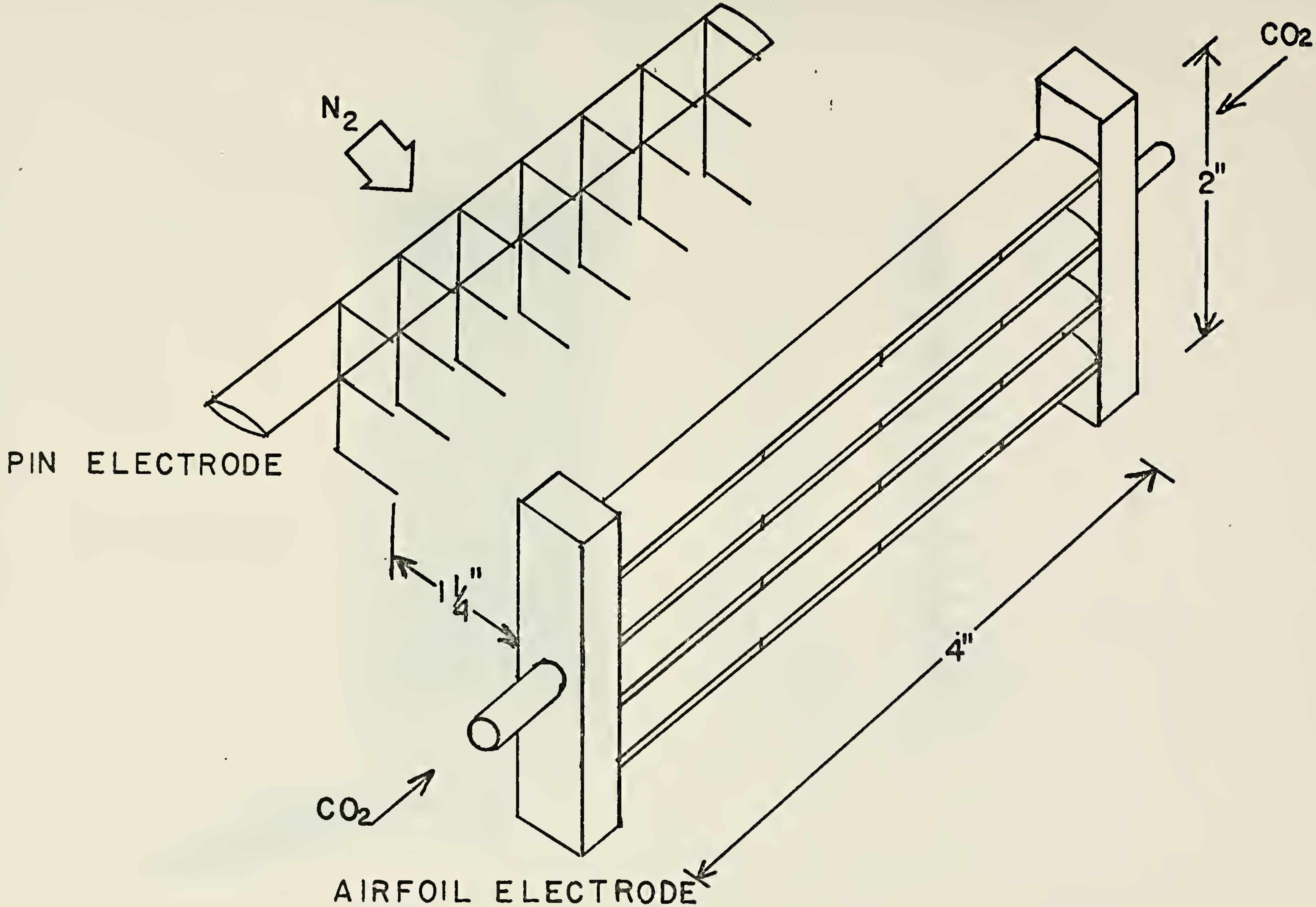


Figure 4. Pin/Airfoil Electrode Design

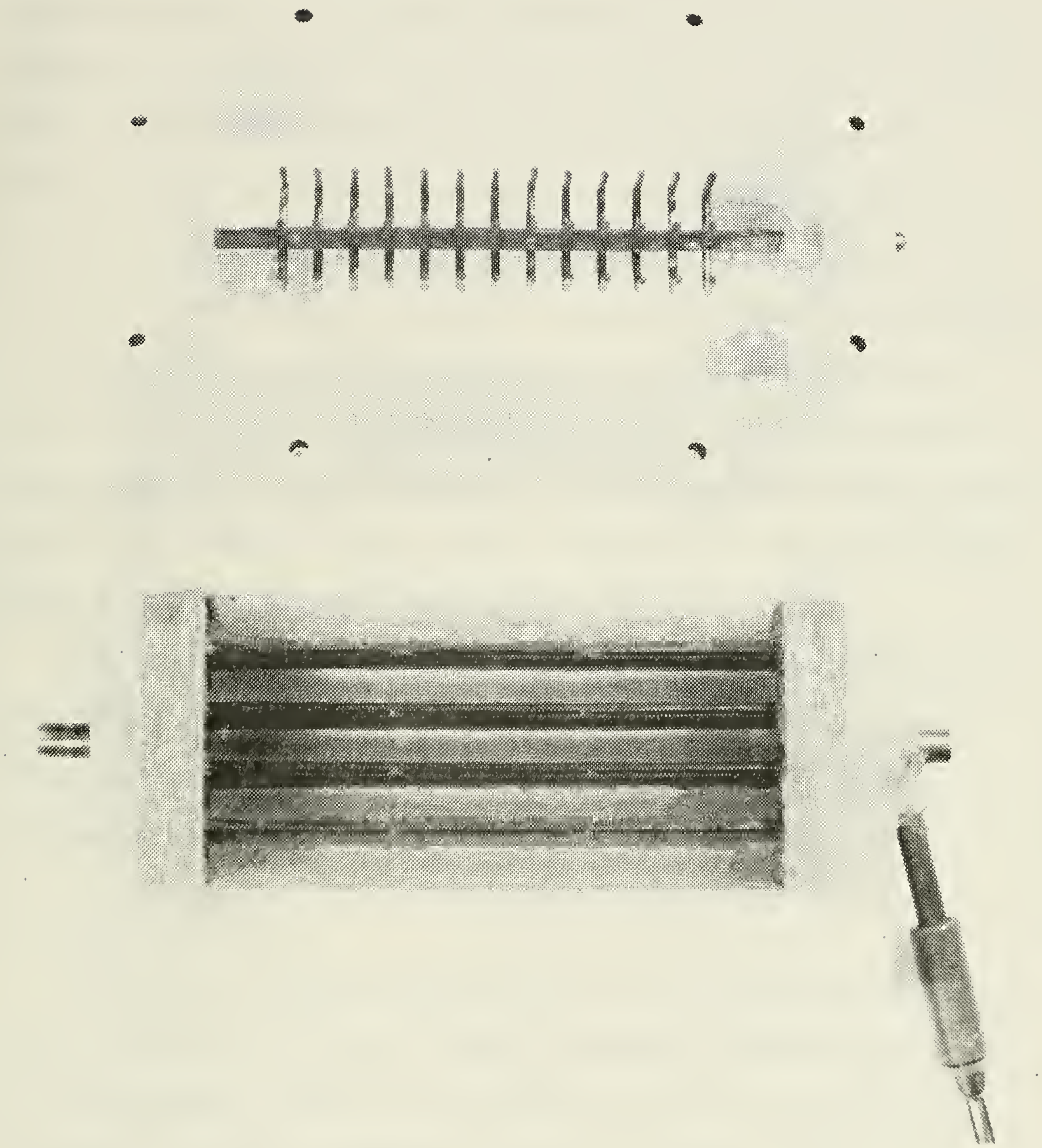


Figure 5. Pin/Airfoil Electrodes

the gain of the laser (Ref. 8). As stated in Ref. 8, if the nitrogen and carbon dioxide are mixed before entering the discharge region and the laser cavity arranged so that the lasing action takes place in the discharge region the gain is about 1/2 percent per cm; if the CO_2 is mixed with the nitrogen dowstream from discharge region and just prior to entering the laser cavity the gain goes up to 4.3 percent per cm. The four hollow airfoils are connected on each end to a common manifold. Each end manifold was connected to the CO_2 supply. The pin electrode was connected to the positive side of the high voltage power supply and the hollow airfoils were connected to the ground side of the high voltage supply through an ammeter during most of the tests reported here.

The power supply used to produce the corona discharge was a Sorensen Electric High Voltage D. C. power supply model number 2060-50 RD rated at 60 kilovolts and 50 milliamperes.

D. LASER SYSTEM

The laser cavity consisted of a 2 x 4 inch plexiglass wind tunnel section with sodium chloride windows mounted at the Brewster angle on each side of the tunnel section. The tunnel section gradually opens in width from 4 to 6 inches and the tunnel height gradually decreases from 2 inches to 1 1/3 inches through the laser cavity as shown in Figures 6 and 7. This was done to increase the active length of the laser medium while maintaining the same area

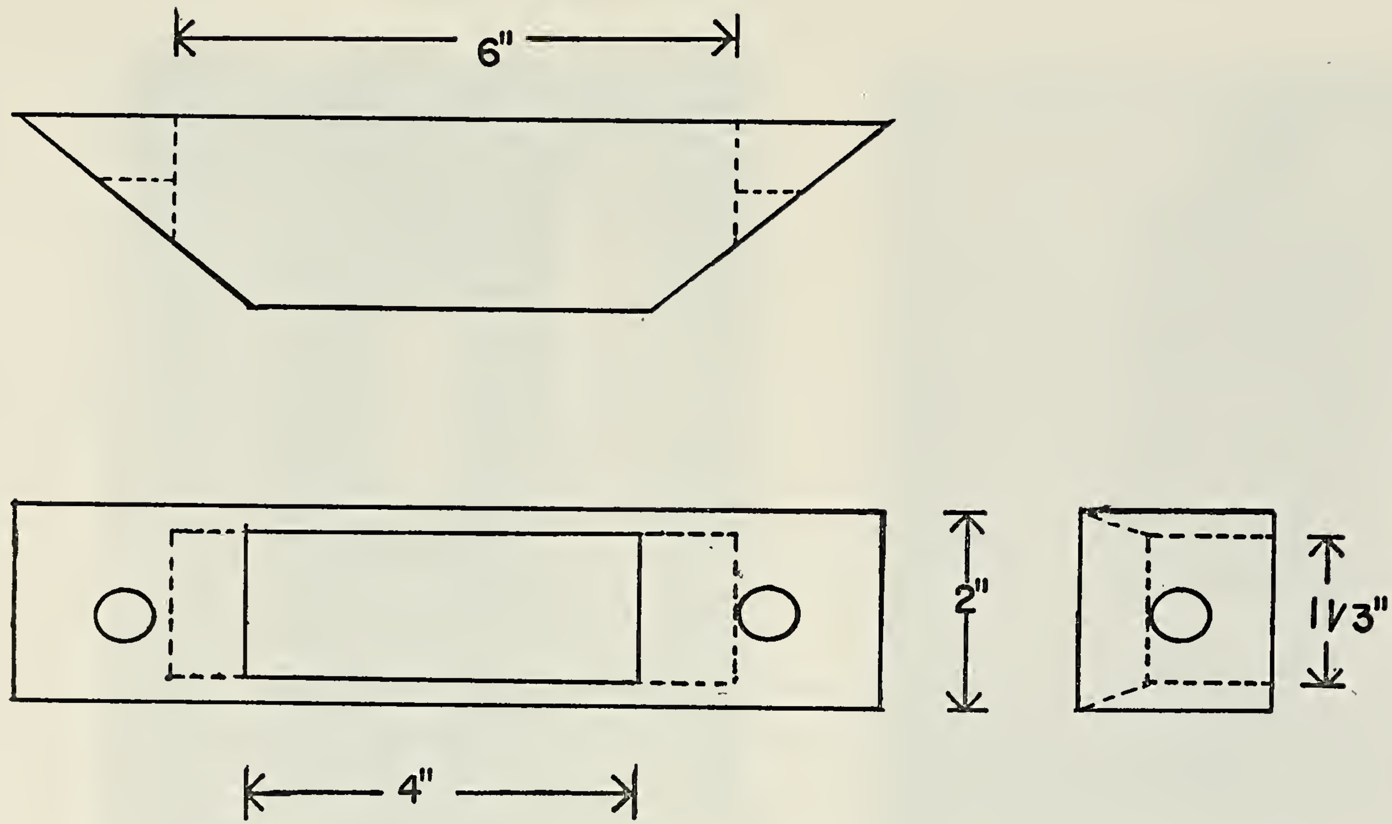
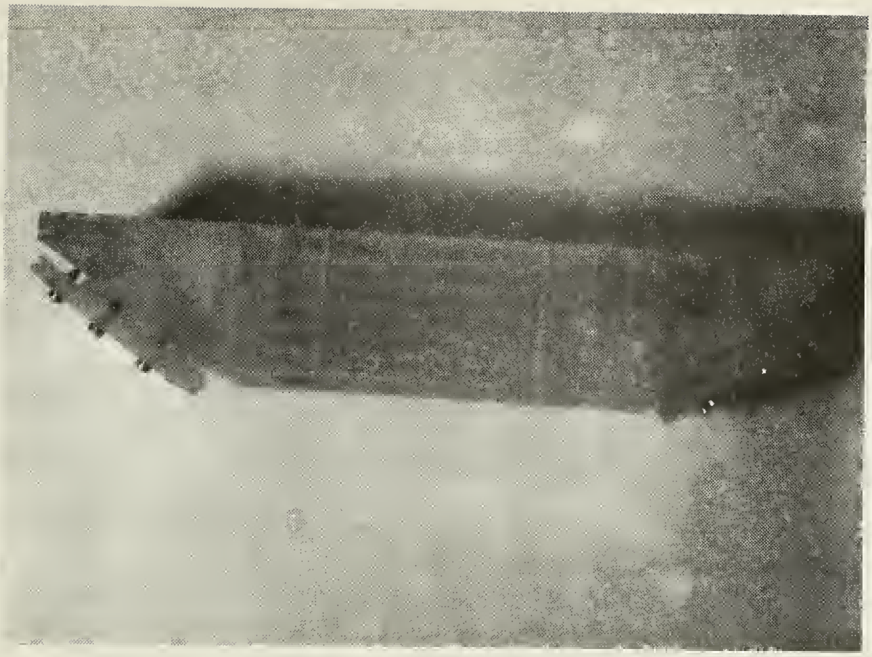


Figure 6. Laser Cavity Section



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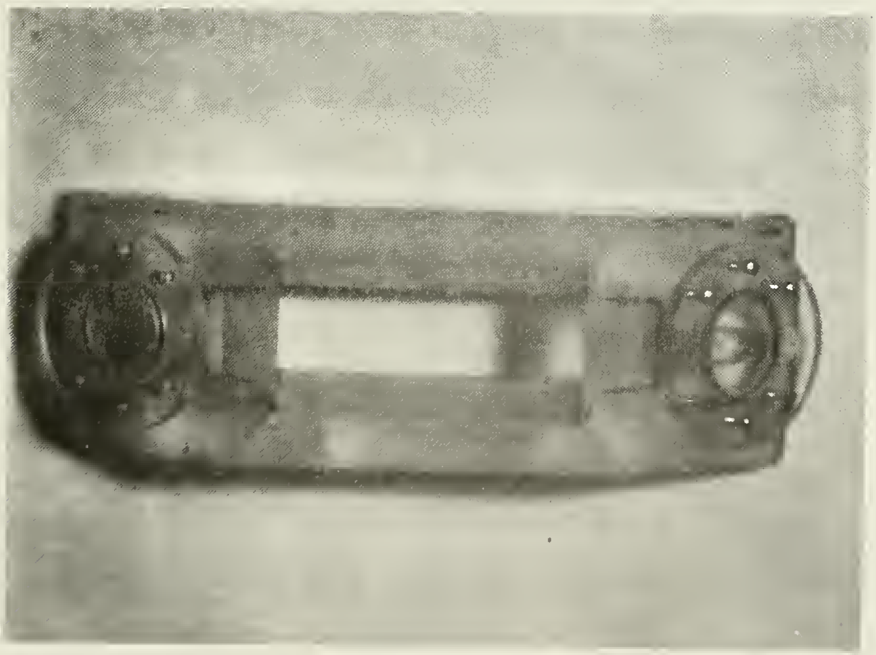

7b

Figure 7. Laser Cavity Wind Tunnel Section.
7a. Top View 7b. Front View

ratio in the tunnel. Figure 8 is a disassembled view of the pin electrode, discharge region, airfoil electrode, and laser cavity section. External to the wind tunnel were mounted two, one-inch diameter gold plated mirrors. One was flat and the other had a focal length of 10 meters. They were separated by a distance of 1 meter and aligned to form the optical resonant cavity. The output coupling consisted of a 2 millimeter hole in the curved mirror.

The laser energy detectors were a pyroelectric detector manufactured by the Barnes Engineering Company, and the Ge-Au detector model number 9213 manufactured by the Santa Barbara Research Center. The detector output was connected to a Tektronic Type 545 Oscillscope. A chopper was used with these detectors. The chopper was set for 100 cycles per second for maximum detector response. Figure 9 shows the optical components. Looking down the optical bench, the detector, chopper, output mirror, laser cavity section, and the end mirror are visible. The high voltage power supply control is in the background.

E. OTHER COMPONENTS

Pressure measurements were made with various mercury and water manometers and Bourdon Gauges. The temperatures were measured using a nickel-iron thermocouple connected to a meter calibrated to read in degrees Fahrenheit. Several Simpson microammeters and milliammeters were used to measure the current flow into the corona discharge.

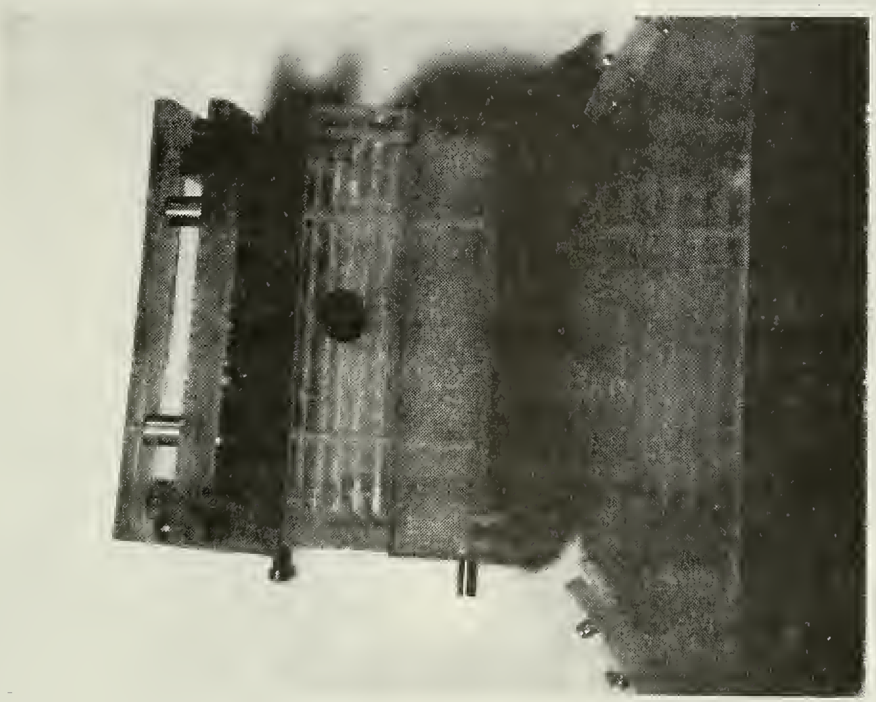

Figure 8. Pin Electrode, Discharge Region, Airfoil Electrode, and Laser Cavity Section.

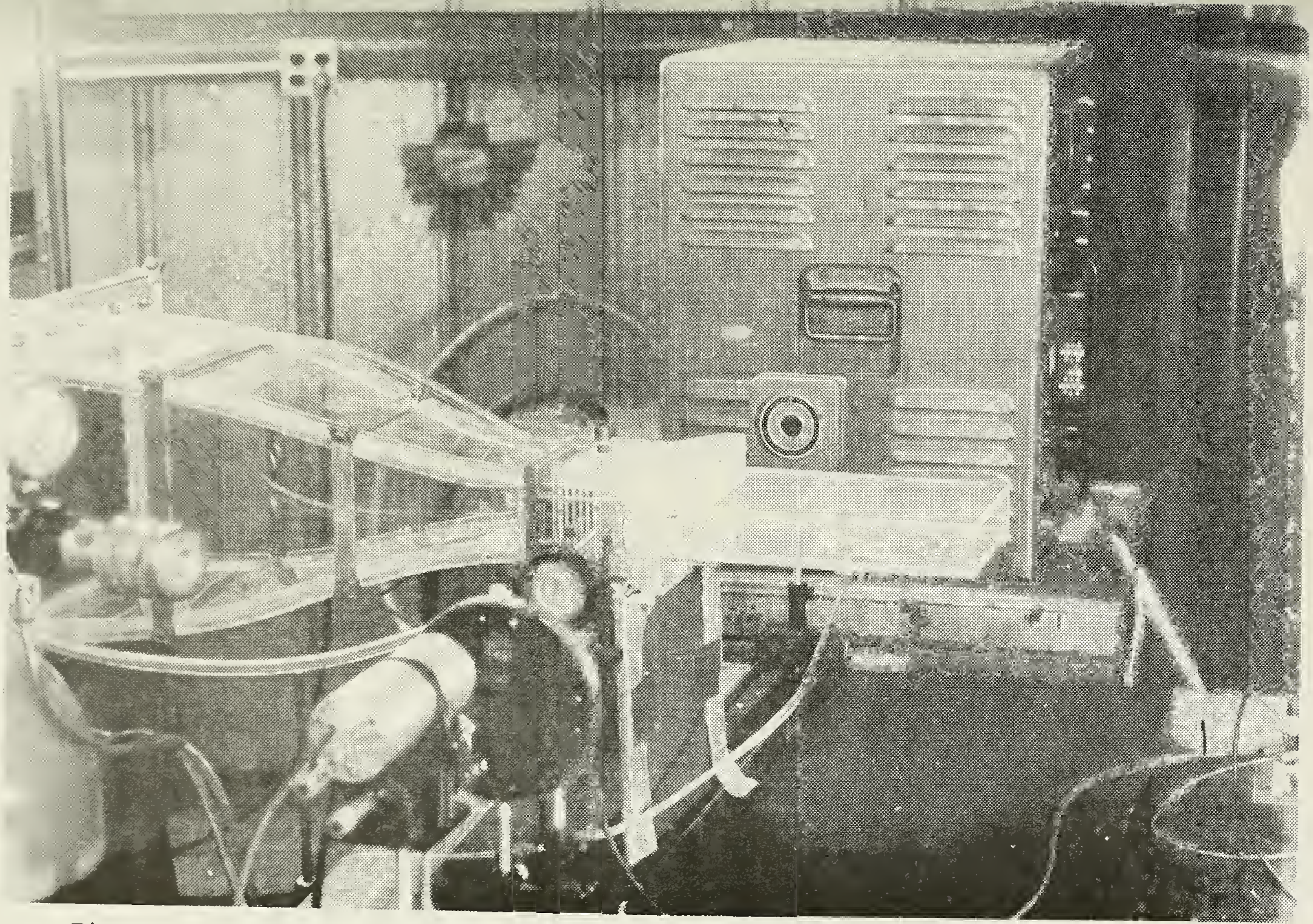

Figure 9. Detector, Chopper, and Laser Cavity Including End Mirrors

III. EXPERIMENTAL PROCEDURE

The experimental procedure was broken into two distinct areas. The first was the corona discharge investigation using air and nitrogen, and the second was the attempt to achieve laser action.

The procedure used to collect current-voltage data in air consisted of using the Carrier air compressor to flow air through the discharge region and to see what effect the two different sets of screens had on the amount of power input to the corona discharge. One screen had a pattern of hexagonal holes and smaller circular holes (Ref. 7). The other screen arrangement tested and ultimately used exclusively is described in Section II. According to Ref. 7, the hexagonal screen had the best turbulence and velocity profile and should therefore be able to sustain the highest power corona discharge. Several attempts were made to determine why this screen did not perform as the turbulence data indicated it should.

The hexagonal screen could not sustain a high power corona, allowing an arc to form along the right hand tunnel wall. A filament would form not from the pins but from the airfoil itself; this filament would follow a pattern very close to the walls. The attempts made to ascertain the reason for this breakdown at relatively low power included spraying the metal screen with an acrylic

high voltage insulation, fabricating a phenolic screen with essentially the same hole pattern as the hexagonal screen, and insulating that portion of the electrodes, which was within 1/4 inch of the tunnel walls. None of these changes brought the discharge performance up to that suggested by the turbulence data. Switching from metal to phenolic improved the performance but it was still not as good as the other screen combination. It was therefore decided to discontinue this investigation and use the screen combination with the highest demonstrated power for the laser attempt.

The next step was to build a blow-down tunnel using bottled nitrogen to test the corona discharge in nitrogen. Since the run time using the blow-down arrangement was very limited the procedure was altered to allow for the maximum use of nitrogen. The discharge region was purged with nitrogen and subsequently the maximum electric power that could be maintained with no flow was applied; then the nitrogen was allowed to flow and the electrical power increased to the maximum sustainable with that flow. The differential pressure transducer drove the Y axis of the X-Y plotter while the discharge current drove the X axis. These data were obtained with a fixed discharge voltage. Several runs were made in this manner at various flow velocities and electric discharge power. This technique for getting current-voltage data at varying flow rates must be further refined to get rid of the noise in the system.

Following the discharge work, attempts were made to achieve laser action. The maximum nitrogen flow velocity was set with the maximum discharge power and then CO_2 was injected and attempts were made to detect laser action. The optics and detector were aligned prior to these attempts. Many factors were present which frustrated the attempts to get the laser to work. The right proportion of CO_2 has to be metered into the flow. The mirror alignment is critical and the output coupling greatly affects the performance of the laser. The detector also is a critical element in this portion of the experiment. The pyroelectric detector used for the initial laser experiments stopped functioning and a Ge-Au detector which was extremely sensitive to static electricity was used for the remainder of the experiments. The Ge-Au detector element is much smaller than the pyroelectric and this makes its alignment even more critical. All of these factors have to be precisely balanced and adjusted to allow laser action and to be able to detect it.

IV. DISCUSSION OF RESULTS

No laser action was detected in either air or nitrogen. Preliminary calculations shown in Appendix A indicate that the small signal gain was very marginal for this laser set-up. Even using the optimistic numbers, the margin of loss after allowing for only 5 percent output coupling was only 1 or 2 percent. It is estimated that the mirrors used had losses that were higher than 5 percent judging from the condition of gold plating on their surfaces. The theoretical spot size predicted for this cavity was about 2 mm and the 2 mm output coupling hole is much too large for this spot size. These two factors contribute more losses than the set-up can tolerate and still oscillate in a stable configuration. These problems were known before the laser experiments were attempted, but since a better set of mirrors was not available, the laser experiment was attempted in the hopes that an unstable mode (Ref. 9) might be set up and some output detected. The run time was long enough for this to occur. Another problem which prevented the laser from oscillating was the low power of the electric discharge. Figure 10 shows the maximum power into the discharge at various flow rates. There does not seem to be any pumping threshold for the CO_2 molecular lasers other than that required to achieve a population inversion (Ref. 20). Other literature indicates,

however, that most of the electric discharge work has a minimum input power of about one kilowatt. Figure 10 indicates that the maximum power available in nitrogen was about 100 watts for an electrode spacing of 3.2 Cm. Figure 11 indicates a maximum power of about 190 watts with the electrode spacing set at 5.3 Cm. The power per unit volume is approximately the same for the two electrode spacings. Figures 10 and 11 show that the power versus flow velocity increases much more rapidly in nitrogen than in air and that reasonably higher flow velocities would allow sufficient power to be coupled into the discharge.

The laser experiment was attempted using nitrogen and then using air. With the maximum flow rate set on the nitrogen and the maximum flow rate set on the carbon dioxide the percentage of CO_2 injected into the flow was about 10 percent by volume which is in the optimum percentage region for this type laser (Ref. 11). With the air flow set at maximum and the CO_2 set at maximum, the percentage of CO_2 was about 2.3 percent by volume. The laser experiment in air was not expected to lase because of the high concentration of water and because of oxygen contamination in the electric discharge (many undersirable O_2 compounds are formed when N_2 and O_2 are passed through an electric discharge). This portion of the experiment was conducted in order to compare the discharge data in air with CO_2 flowing to that without the CO_2 flowing.

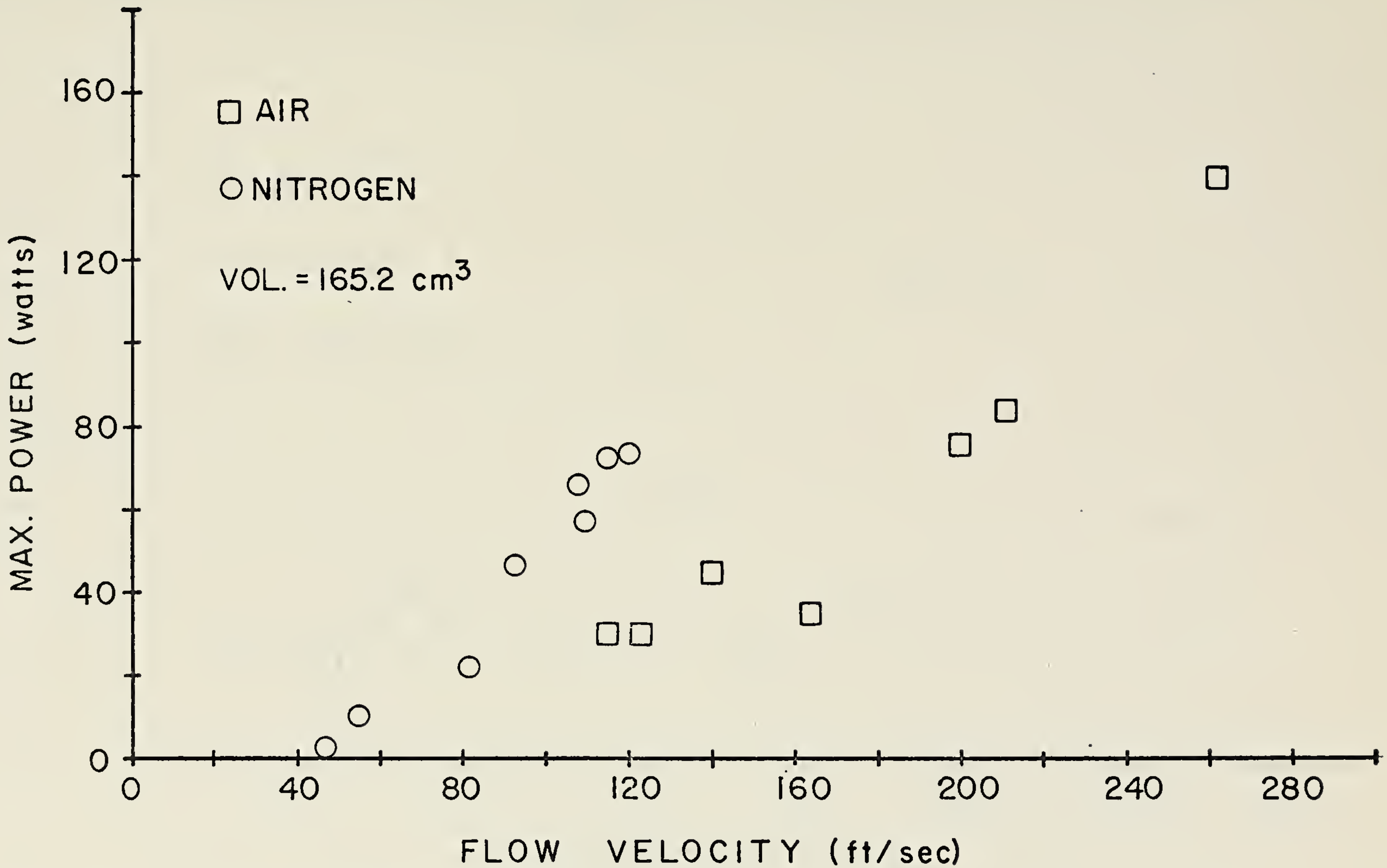

Figure 10. Discharge Power Versus Flow Velocity, 3.2 cm Electrode Spacing

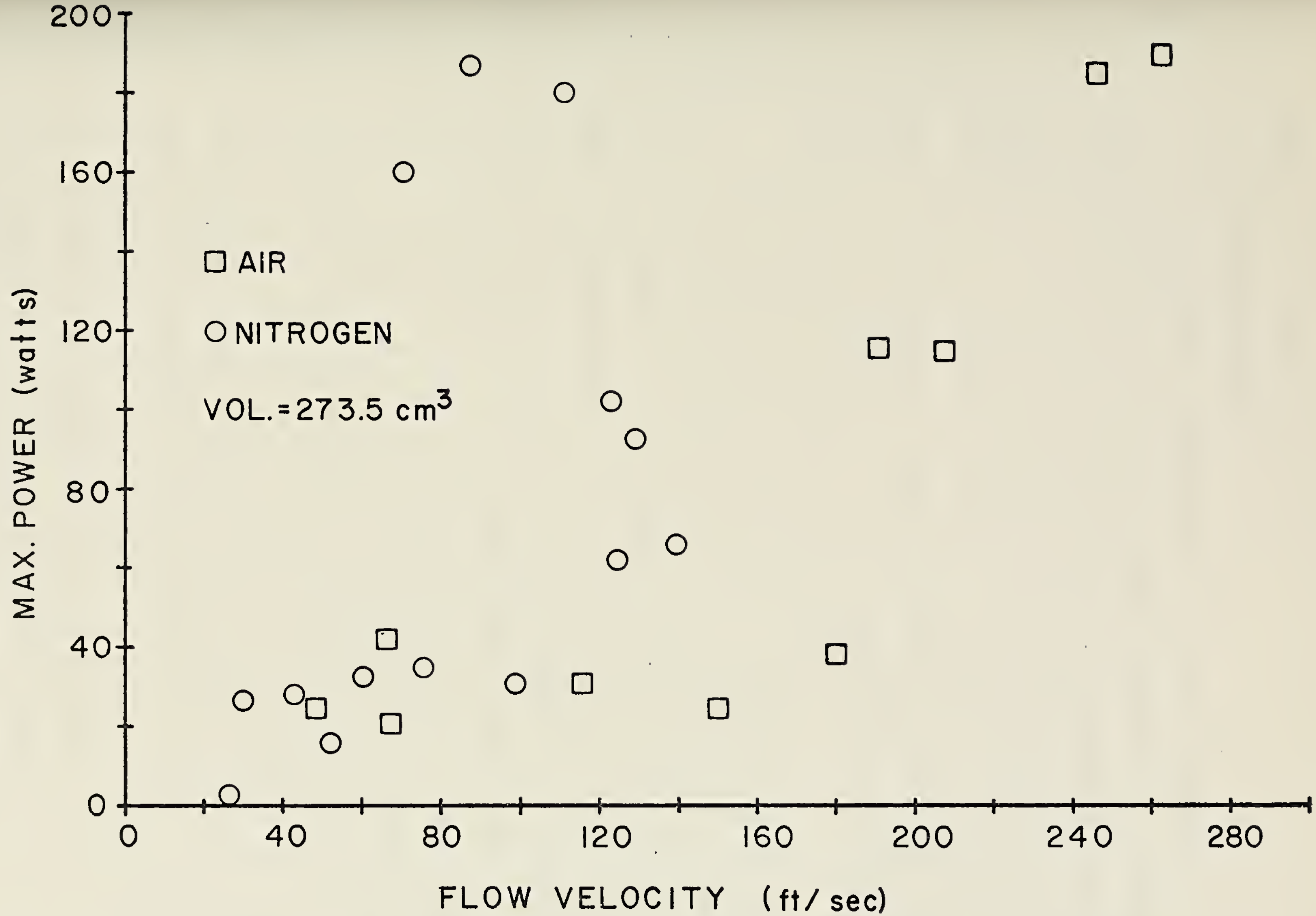

Figure 11. Discharge Power Versus Flow Velocity, 5.3 cm Electrode Spacing

There was no difference within the statistical accuracy of the discharge data.

An additional experimental procedure would be to obtain a CO_2 laser and see if the medium could amplify the output of this laser demonstrating that the pumping scheme is adequate but that the overall small signal gain is not sufficient to support a laser oscillator. No portable CO_2 laser was available, however, during the time that the system was configured in such a manner as to be able to conduct laser amplifier experiments.

One experimental quirk which arose during an attempt to run the electric discharge with the polarity reversed (the pins negative rather than positive) was both encouraging and baffling. All of the discharge data in air had been taken with the pin electrode positive. With the polarity reversed in air very little power could be coupled into the corona before breakdown occurred, however when the polarity was reversed in nitrogen the discharge power increased very dramatically but only two, three, or four pins of the thirty-nine seemed to be carrying the current. The current being carried by these pins was very visible even in the daylight and it amounted to about 4 mA per pin. The discharge was run at night in total darkness and all that could be seen were very bright spots of light coming from three of the four corner pins or from all four corner pins and occassionly from only two diagonal corner pins. When the corona discharge in air was run at night with

the pins positive the whole test section glowed which is the discharge mode desired. Why these few pins in nitrogen with the negative polarity can sustain such high currents without breaking down the nitrogen is not understood, but if all the pins could be made to conduct in this manner very high power coronas would result. Some attempts were made to make all the pins conduct without success. Reference 12 uses the same electrode configuration but does not indicate having this problem. They may not have reversed the electrode polarity or the fact that their pins were individually ballasted may have prevented the problem from occurring. References 13 and 14 were consulted without finding a definite reason for the pin electrode to behave this way.

V. RECOMMENDATIONS

The first recommendation is to try the laser amplifier experiments described in Section IV. If the results indicate that the laser pumping scheme is adequate then more effort should be expended to correct the deficiences of the present system also described in Section IV.

It is felt that two basic components are necessary to make this system lase. A compressor is needed for higher gas flow rates. The compressor mentioned in Ref. 7 would be adequate. Using eight bottles of nitrogen gave a useful flow time of approximately one minute but at about one third the flow velocity really needed. A closed cycle system would allow the higher flow rate without exhausting large quantities of gas. The second component needed is a good set of mirrors. The best mirrors available have reflectivities of the order of 99.9 percent for 10.6 micron radiation. A set of these mirrors with the output coupling from one of them of about 5 percent would allow a marginal system to lase.

A third component, a more sensitive and stable detector, would be desirable but is not essential. The detectors used were connected directly to the Tektronic oscilloscope using a 1A6 plug-in unit whose maximum sensitivity was 1 mV/cm. The detector could be wired into a linear amplifier and then into the oscilloscope or a more sensitive

plug-in unit could be used. This was not done because the pyroelectric detector would not drive the linear amplifier and it was not wired for the differential input required on the more sensitive plug-in unit available. By the time it became evident that the detector may not be sensitive enough to pick up the anticipated output and before the necessary wiring changes could be made, it stopped functioning and reasons for the failure could not be found. The Ge-Au detector had been previously wired for use with the 1A6 plug-in unit and its noise sensitivity was such that a more sensitive plug-in unit would have been saturated with noise and therefore of no help.

There is much effort still needed in understanding the discharge mechanism. The reason for the high power but low disturbution with the pin electrode connected negative is intriguing and could result in some very significant power increases if all of the pins could be made to carry the amounts of current that these few pins were carrying without breaking down.

It is still felt that for high power application, a simple, inexpensive, powerful laser can be built using the turbulence-stabilized electric-discharge convection laser in closed-cycle system, and that its construction should be attempted.

APPENDIX A

LASER THEORY

The theory presented here is that laser theory applicable to atmospheric-pressure, electric-discharge lasers. The theory of the CO_2 laser and the resonate cavity stability calculations are explained in several texts, Ref. 4 for example.

In Ref. 15, a plot of excitation efficiency versus the electric field to pressure ratio for two mixtures of He, N_2, and CO_2 can be found. One of the curves has a ratio of 1:7:0, CO_2:N_2:He which is close to the CO_2:N_2 ratio used in these experiments. The optimum value of E/P is approximately 11 volts per cm per torr. The discharge arrangement used gave an E/P ratio of anywhere from 7.45 to 14 Volts per cm per torr depending on the electrode separation. The curve in Ref. 15 has a broad maximum and indicates about 80 percent or greater excitation efficiency for E/P's ranging from about 5 to about 20 Volts per cm per torr. This indicates that the corona discharge electric field to pressure ratio is nearly optimum for this EDCL. In other words, nearly all of the input power which can be theoretically converted into laser power will be if other conditions are met perfectly. The amount of input power is dependent on the amount of current that can be pumped into the discharge while

maintaining the optimum E/P ratio. This is one of the shortcomings of our experimental set-up. The power desired was around 1 kilowatt while the power finally obtained using the N_2, CO_2 mixture was 190 watts.

Another factor affecting the laser performance is the small signal gain. Reference 1 gives the following general small signal gain equation for electric discharge convection lasers:

$$g = K(P_e/V)/P^2 \qquad \text{A1}$$

P_e - electrical power input in watts.

V - volume in cubic cm.

P - pressure in torr.

where K = 3 cm^2 $torr^2$/watt for a discharge specific power of 200 kw per lb/sec independent of the operating pressure. It has been verified experimentally for pressures between 20 and 40 torr.

This gain equation is appropriate for low pressure lasers. Experimental verification of its applicability at high pressure is not evident in the literature.

In order to have a laser oscillator the factor exp(g(x)) must be greater than one by at least the same factor as the losses in one pass through the laser medium. If this factor is not equal to one plus the losses the cavity can not sustain oscillations. For this laser using a representative input power exp(g(x)) is 1.00003 for x equal to 30 cm.

Reference 16 gives the laser losses for a cw CO_2 laser using gold mirrors and salt windows as 9.3 percent

per pass independent of laser power. These preliminary calculations show that the EDCL will not lase with the power input available and Equation A1 will require prohibitively high powers for a laser operated at atmospheric pressure to lase or else the laser will have to be extremely long which is impractical for the EDCL.

References 17, 18, and 8 indicate gains from 1.0 percent per cm up to 5 percent per. cm. for high pressure lasers. Reference 17 gives the pressure dependence as being inversely proportional to the pressure to the first power rather than to the pressure squared. Using these gain figures and an active length of 15 cm the EDCL should work provided sufficient discharge power is available and the output coupling is reasonable, around 5 percent.

APPENDIX B

LASER ALIGNMENT

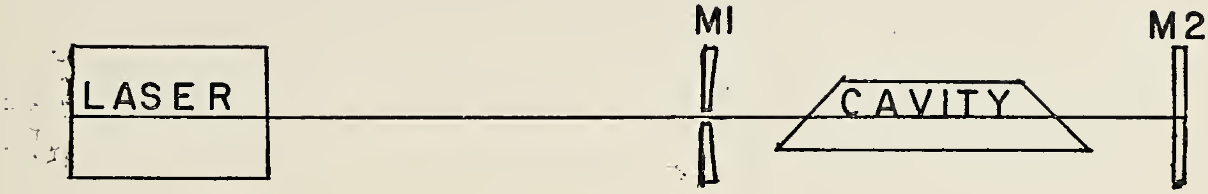

Figure 12. Laser Cavity Alignment

Laser Alignment

1. Adjust the alignment laser beam so that it passes through the center of the cavity section optical axis with M1 removed.

2. Adjust M2 so that the laser beam is reflected back on itself. Install M1 and adjust so that the laser beam passes through the output coupling hole. Align M1 so that there is only one spot on M2.

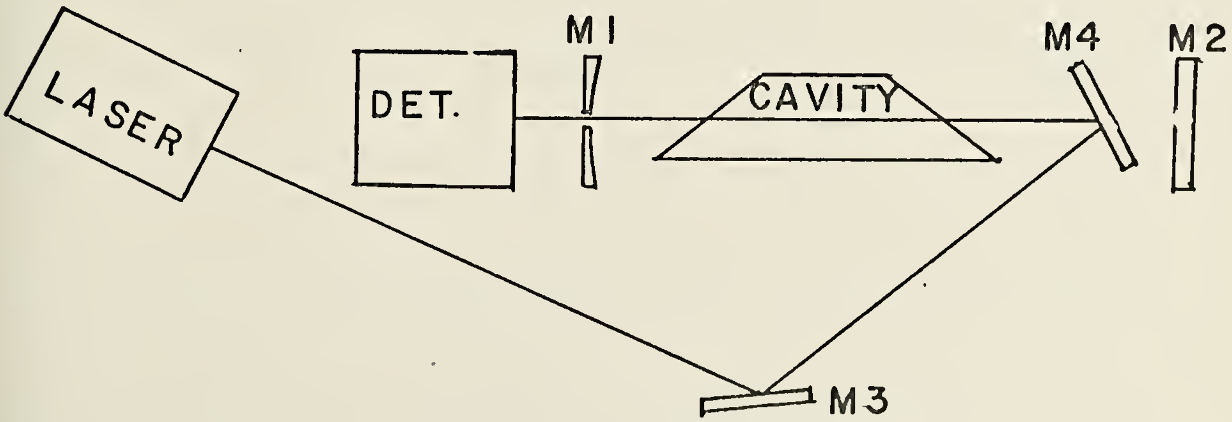

Figure 13. Detector Alignment

3. Install the detector on the output side of M1 and using the auxiliary mirrors M3 and M4 reflect the laser beam back through the cavity and through M1 into the detector.

4. Adjust the detector so that the laser beam is centered on the detector element.

5. Remove auxiliary mirror M4.

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